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No. 414

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AERODYNAMIC LABORATORY AT CUATRO VIENTOS

By Moreno Caracciolo

From "Boletin Oficial," Royal Aero-Club of Spain  
Second Quarter, April-June, 1924  
and  
"L'Aéronautique," September, 1926

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Washington  
June, 1927

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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AERODYNAMIC LABORATORY AT CUATRO VIENTOS.\*

By Moreno Caracciolo.

The science of mathematics has enabled scientists to express in formulas and graphs the origin and development of physical phenomena. The benefits accruing to humanity from these mysterious symbols are incalculable. Sometimes, however, the desire to confine mathematics to the stubborn truth has yielded to the creation of erroneous formulas and theories, which have retarded progress instead of promoting it.

Aerodynamics affords one of the clearest examples of this prejudicial effect of ill-considered theories and wrong formulas. An exponent added to a trigonometrical line, a sine raised to the second power, was the obstacle interposed by the genius of Newton before the progress in aeronautics. According to the celebrated and erroneous formula of the English philosopher, 3.5 m-kg (25.3 ft.-lb.) are required to support in the air a surface of 1 m<sup>2</sup> (10.76 sq.ft.) when, in reality, only one-fifth as much energy is required. Scientists who deduced the absurd results of Newton's formula, preferred to invent marvelous biological forces to explain the undeniable action of animal flight, rather than resort to facts to confirm or correct the

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\* "El laboratorio aerodinamico de Quatro Vientos," "Boletin Oficial," Second Quarter, April-June, 1924.



results of scientific hypotheses and mathematical calculations. The internal combustion engine has solved the problem of mechanical flight and, even if Newton had removed the exponent from the sine of the angle of attack, airplanes and airships would not, for that reason, have furrowed space, dragged along by the giddy whirl of their propellers. The way of the air would have appeared to man, however, more open and unobstructed and perhaps soaring flight, which has followed mechanical flight, would have been its predecessor and guide.

For this reason, after being suddenly called to reality by the Wright Brothers in flying contrary to the canons of science, <sup>it</sup> could not be developed by mathematical reasoning, without investigation, in each case, as to whether the theoretical results were correct or not.

Thus aerodynamical laboratories came into existence, the first one in the shadow of the Eiffel tower, and subsequently others throughout the civilized world. One was constructed in Madrid through the initiative and under the direction of Commander Herrera, who introduced reforms and improvements which make it one of the best.

An aerodynamical laboratory consists essentially of a large tube through which a strong current of air is forced by a powerful propeller. The object to be tested (an airplane model, a wing profile, etc.) is placed inside this tube and a special balance measures the pressure exerted on it by the wind, while an anemometer indicates the velocity of the wind.



The wind tunnel of the Cuatro Vientos laboratory has the largest diameter (3 m = 9.84 ft.) of any in the world and is of the closed type. In tunnels of the open type, the propeller draws in the free air and sends it through the tube, which discharges it into the atmosphere at the other end, after the balance has measured the pressure exerted on the object being tested. In Herrera's tunnel, as shown in Fig. 3, the air follows a closed circuit and is drawn in again by the propeller, after it has acted on the balance. The resultant of the wind pressure is accurately measured in both magnitude and direction by an aerodynamic balance designed and constructed by Herrera, and which we will briefly describe.

A heavy steel frame is supported on three wheels with horizontal axes,  $Z_d$ ,  $Z_l$  and  $Z_c$ . The downward pressure of these wheels, when the wind acts on the surface of the model which is rigidly attached to the frame, enables the determination of the vertical component of the air pressure. The pressure exerted horizontally, by two other wheels,  $X_d$  and  $X_l$ , mounted at the ends of two horizontal bars, gives the horizontal component of the wind pressure. Knowing the values of these two rectangular forces, the direction and magnitude of their resultant  $R$  is easily calculated.

This resultant may, however, fall outside the vertical plane passing through the axis of the tunnel. It is not then sufficient to know its vertical component and its horizontal



component in the direction of the axis of the tunnel. It would also be necessary to know a third component, normal to the axis of the tunnel, in order to form the parallelopiped of forces and determine the magnitude and direction of the resultant. A few simple arithmetical operations (the application of the theorem of equality of moments to the three rectangular axes) enable us to determine the exact values of the three components, provided we can measure the pressure exerted downward or horizontally by the five wheels. These wheels rest on disks supported by balls, which in turn are supported by pistons fitting perfectly in cylinders filled with mercury. The pressure exerted on the wheel is transmitted to the mercury, which rises in a graduated column connected with the cylinder.

From the five cylinders (three vertical and two horizontal) tubes lead to the five graduated columns, as shown in Fig. 3. An observer notes the values of the pressures and takes an instantaneous photograph of the five columns, if it is desired to determine accurately the simultaneous values of the five components.

The photograph serves, moreover, to determine the velocity of the wind, by means of an anemometer invented, like the balance, by Commander Herrera. This instrument consists of a double tube which opens into the upper part of the tunnel. One end enters the air stream, producing a pressure. In the other end (parallel to the wind) a negative pressure or suction is



produced. In the lower part of the tube there is a colored liquid, which follows the oscillations of the air flow, rising in the branch in which the suction is produced and descending in the branch subjected to the pressure increase. The velocity is measured on a scale connected with this part of the tube.

The disadvantages of this system, as employed in the Göttingen laboratory, are apparent. The height of the liquid depends on the pressure of the wind and is proportional to the square of the velocity. Designating the height of the liquid by  $z$ , the velocity by  $v$  and a proportionality factor by  $k$ , we have

$$z = k v^2 \qquad dz = 2 k v \, dv \qquad dz/dv = 2 k v$$

For any increase  $dv$  in velocity, there is a corresponding increase  $dz$  in the height of the liquid. It is very small and difficult to estimate, when  $v$  is small. It is very great and requires a very long tube, when  $v$  is large.

In the Eiffel laboratory this difficulty is avoided by using four tubes instead of one. Each tube has a different inclination, one being vertical, another having a slope of 0.5, another of 0.25, and another of 0.1. A change of 1 cm (0.4 in.) in the level of the liquid means an advance of 10 cm (about 4 inches) in the last tube, which can therefore be used for small velocities, while the other tubes can be used for greater velocities.



More ingenious is the device adopted by the Italian "Istituto Experimental Aeronautico" of using a tube bent into quarter of a circumference, in which the more sloping portion is automatically filled by small increases in the level of the liquid and the more vertical portion only by greater increases. The sensitivity of the apparatus, however, is not the same for all velocities.

In the Cuatro Vientos laboratory, the lower portion of the anemometric tube is also curved; not, however, in the quarter of a circumference, but in such a form that the sensitivity has an absolutely constant value for all velocities. The increase  $ds$ , in the length of the portion of the tube filled by the liquid is proportional to the increase in velocity, or

$$ds/dv = C;$$

but, since

$$z = k v^2, \quad v = \sqrt{z/k},$$

and, for the whole,  $dv = \frac{dz}{2\sqrt{kz}}$ .

The constant ratio  $ds/dv$  can therefore be expressed by the equation  $\frac{ds}{dz} = \frac{C}{2\sqrt{kz}}$  which is the differential equation of a cycloid with a horizontal base referred to the vertical at its lowest point, like the axis  $z$ , and whose generating circle has the radius  $gk$ . The maximum ordinate of this cycloid is determined by knowing the maximum wind velocity (60 m, or about 200 ft., per second) and the value of  $k$  corresponding to ab-



soluble alcohol, the liquid used in the anemometer. By this ingenious device, Herrera obtained an anemometer of constant sensitivity and found a new application of the cycloid.

The balance and the anemometer render it possible to investigate the head resistance or drag offered to the wind by all the parts of an airplane and the lift produced by the wings. The propeller is another very important part which must be thoroughly understood. The Cuatro Vientos laboratory also has an original and unique device which renders it possible to determine the propeller torque by a single reading.

The propeller shaft is supported on two ball bearings on an iron stand (Fig. 6). The propeller is not shown in the figure. The propeller is driven by means of a chain and cogwheels, by an electric motor, which is fastened to the floor at the left of the figure. When it is not desired to find the torque, the two cogwheels (one on the motor shaft and the other on the propeller shaft) are united directly, as on a bicycle. In the Cuatro Vientos apparatus, however, the chain follows a more complicated path, due to the other cogwheels, one of which is attached to the stand a little below the propeller shaft, and one which can slide between two iron guides extending obliquely from the wall to one of the legs of the stand. A third cogwheel, suspended like a movable pulley, carries a weight of 400 kg (882 lb.) and holds the two parts of the chain taut and parallel. As shown in Fig. 6, the lower side of the chain runs



in a straight line from the motor shaft to the wheel just below the propeller shaft, while the upper side of the chain forms an obtuse angle with its vertex on the wheel which slides on the iron guides. The latter wheel is connected with a 1000 kg (2205 lb.) weight (represented by the rectangle at the left of Fig. 6) by means of a cable passing over a fixed pulley. The resultant of the equal stresses on the two parts of the chain which form the obtuse angle must equal the weight of the counterpoise (minus a certain component of the weight of the movable cogwheel and its accessories), when the counterpoise is in equilibrium. Since the tension on the chain is proportional to the propeller torque, for each value of this torque there is a corresponding position of the sliding wheel. Hence the torque can be read directly by means of a suitable scale attached to the guides of this wheel.

In closing, we will describe the aerodynamic balance invented by Captain of Engineers, Jenaro Olivie, a collaborator of Herrera, which functions with surprising accuracy in the Cuatro Vientos laboratory. If we hold one side of a jointed parallelogram with one hand and pull the opposite side with the other hand, the parallelogram will evidently be distorted and the two remaining sides will assume the direction of the force applied by our hands. If, instead of holding the first side with the whole hand, we hold it with two fingers in such a way that it can rotate about the point held, we can easily counterbal-



ance the rotational moment by applying a suitable weight at a certain distance from the parallelogram. These are the two principles which Captain Olivie applied in his balance.

Fig. 8 shows a wing section or profile S, rigidly attached to the upper horizontal side of a jointed parallelogram G, and an arrow R, which represents the pressure exerted on the profile by the wind. The other two sides of the parallelogram have automatically assumed the same inclination as the air pressure and render it possible to determine easily the value of the angle formed by the latter with the horizontal or with the vertical.

It is necessary to determine the numerical value of the air pressure and, for this purpose, to resort to another jointed parallelogram with two horizontal sides having the same direction and magnitude as in the first parallelogram and with two vertical sides jointed to the non-horizontal sides of the first parallelogram. The second parallelogram rests one of its upper vertices on a support which is represented in Fig. 8.

The pressure of the wind on the wing profile makes it oscillate about this point, unless offset by a movable weight on an extension of the upper horizontal side. By knowing the value of this weight and its distance from the supporting point, we know the value by which the first parallelogram has been distorted. A simple geometrical measurement (the distance of the supporting point from a vertex of the second par-



allelagram) enables us to determine the lever arm of the vertical component and to deduce the exact value of the latter.

We have confined ourselves to a rapid exposition of the most salient and original points and to the unique things in the laboratories of the world.

Translation by Dwight M. Miner,  
National Advisory Committee  
for Aeronautics.



## A p p e n d i x \*

## The Olivié Fineness Balance

This balance, invented by Captain Olivié, renders it possible to obtain automatically the aerodynamic fineness curve of the model (Fig. 8).

The model  $S$ , is attached to a carriage resting on a jointed parallelogram  $G$ , which is balanced in such manner that its equilibrium is neutral when the air is at rest. On beginning a test, the air flow produces on  $S$  a reaction  $R$ , always inclined backward. The jointed parallelogram adopts such a position that its more or less vertical sides form the same angle  $\beta$  with the vertical as is formed by  $R$ . The trigonometric tangent of this angle measures the fineness of the model. The angle  $\beta$  can be measured directly, for each position corresponding to a given angle of attack of the model, with the aid of a graduated dial, and the trigonometric tangent can be calculated, but it is simpler and better to obtain directly the curve which represents the trigonometric tangents of  $\beta$ , i.e., the finenesses in terms of the angle of attack of the model.

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\*This description is taken from an article by Moreno Caracciolo in "L'Aéronautique," September, 1926, pp. 295-296.



This angle of attack  $\alpha$  changes when the pulley P, is rotated, on which is wound the iron wire whose position determines the angle of attack. A screw which turns with the pulley, causes to move parallel to its axis, a nut carrying a pencil which rests on a sheet of paper on the surface of a cylinder whose axis is the axis of rotation of the jointed parallelogram. When the pulley turns, the angle of attack of the model changes in proportion to the displacement of the nut and of the pencil. The paper moves in a direction perpendicular to the motion of the pencil and its displacements are proportional to the successive values of  $\tan \beta$ . Thus the pencil draws the desired curve which has for its abscissas the angles of attack, and for its ordinates the corresponding finenesses.

In this method, however, there would be an appreciable cause of error, if the precaution had not been taken to balance the drag due to the supports, iron wires, etc., outside the model itself. This balancing is done in a very simple and ingenious manner, by placing a small surface  $s$ , normal to the wind and securing it to the lower side of the parallelogram in such a way that its drag is exactly equal to the sum of the parasitic drags, their moments being equal and opposite with respect to the axis of rotation. The correct compensating surface for each case is determined by a preliminary experiment, during which the model is removed, all the supports remaining in place, while gradually changing said surface till



neutral equilibrium is established.

Fig. 14 shows the fineness curve obtained in testing a very good airfoil with the Göttingen profile No. 358. The two tracings correspond to the double ascending and descending course which always constitutes a complete test. The best fineness (of about  $1/20 = \tan \beta$ ) is between  $-8^\circ$  and  $+2^\circ$ .

In order to find the magnitude of the reaction  $R$ , of which only the direction is thus known, another test is made by adding to the compensating or balancing surface another perfectly calibrated surface. The curve then traced by the pencil is that of the ratio between the vertical component of  $R$  and the difference between its horizontal component and the supplementary drag. Hence, we have for each angle of attack, two equations into which enter the two components of the reaction  $R$ . These components can be calculated immediately or obtained by a simple graphic process, discovered by Commander Herrera.

Translation by Dwight M. Miner,  
National Advisory Committee  
for Aeronautics.



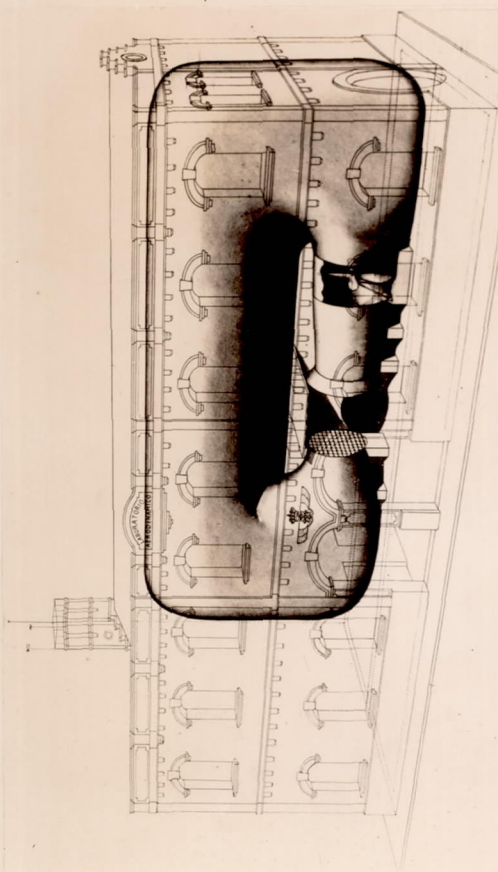


Fig. 1 Composite picture of building and wind tunnel, showing honeycomb and propeller.

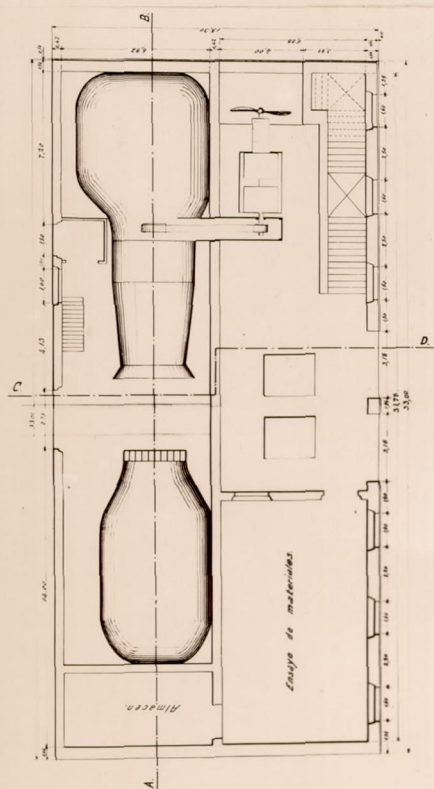


Fig. 2 Ground plan of laboratory, storeroom, Material-testing room.

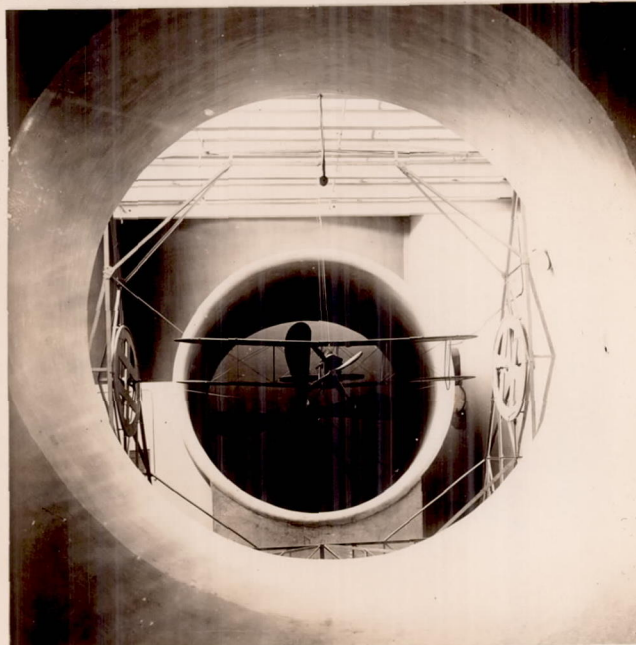


Fig. 4 Interior view of tunnel, showing model and propeller.

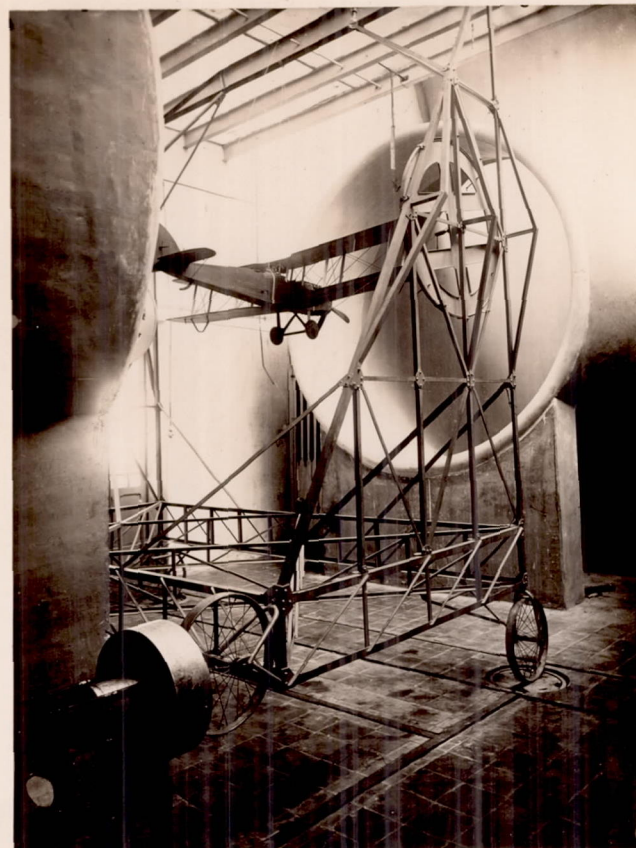


Fig. 5 Aerodynamic balance, showing one wheel transmitting vertical pressure and one wheel transmitting horizontal pressure. Mercury columns shown at left.



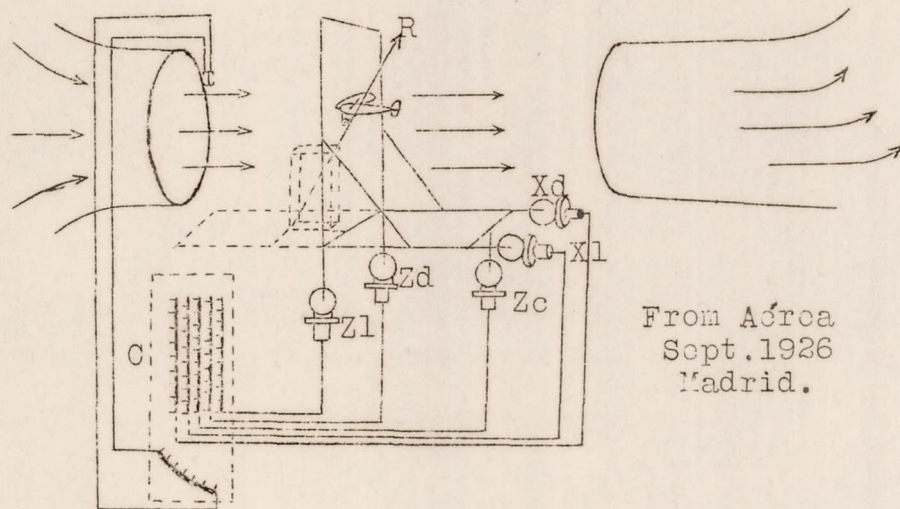


Fig.3 The Herrera aerodynamic balance, Pressure of the 5 wheels supporting the balance are shown by the manometer columns at the left.

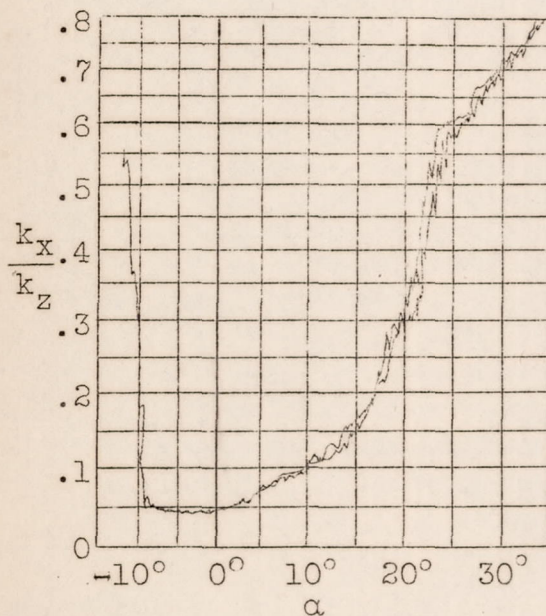


Fig.14 Fineness curve of Göttingen profile 358, as obtained with the Olivie' balance.

From L'Aéronautique  
Sept. 1926.

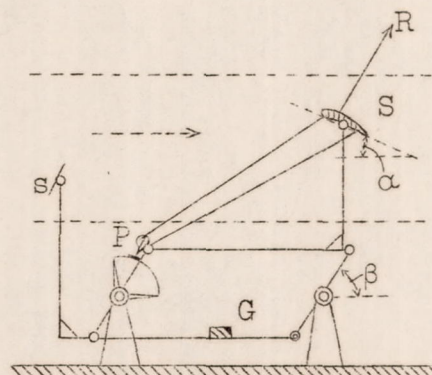


Fig.8 Olivie' balance for measuring the fineness ( $k_x/k_z$ )



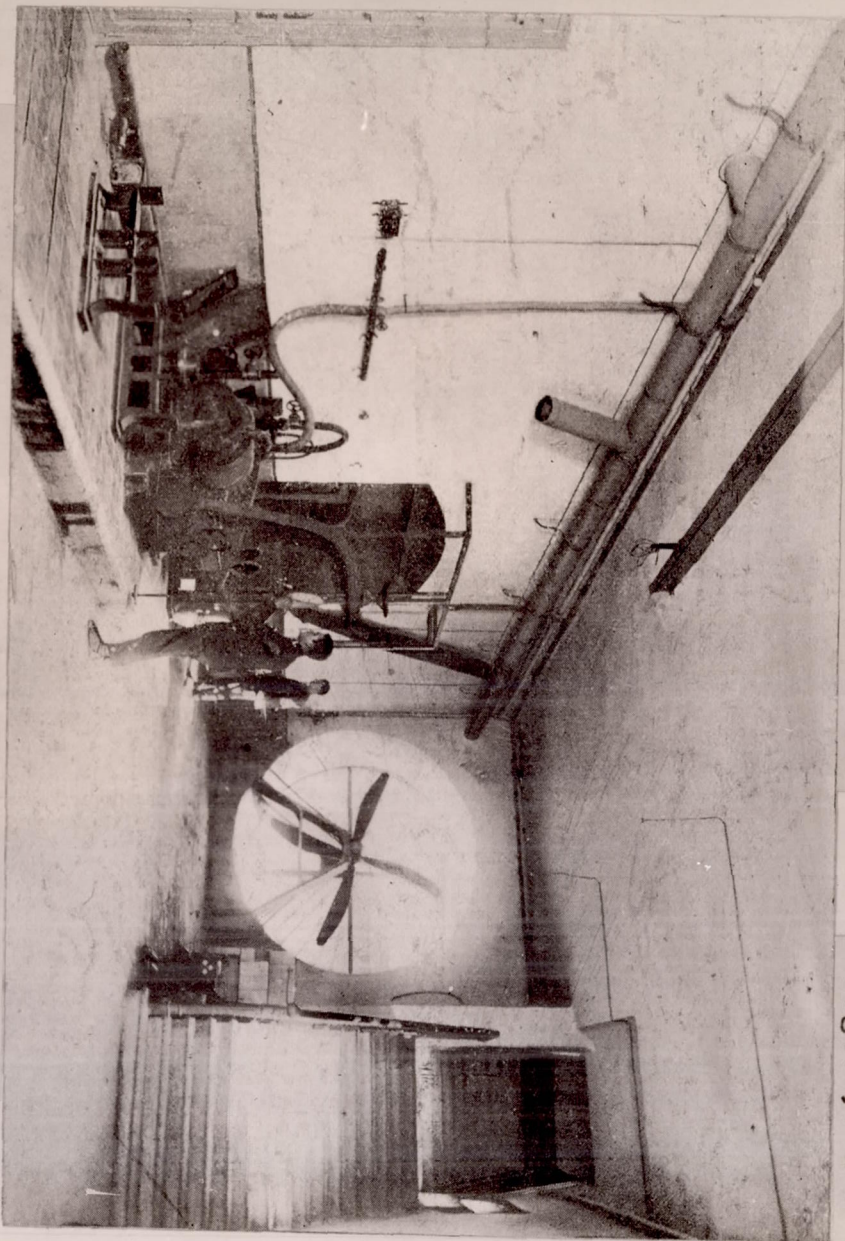


Fig. 7 700 HP. engine which drives the propeller. "Parmetro" in the distance.

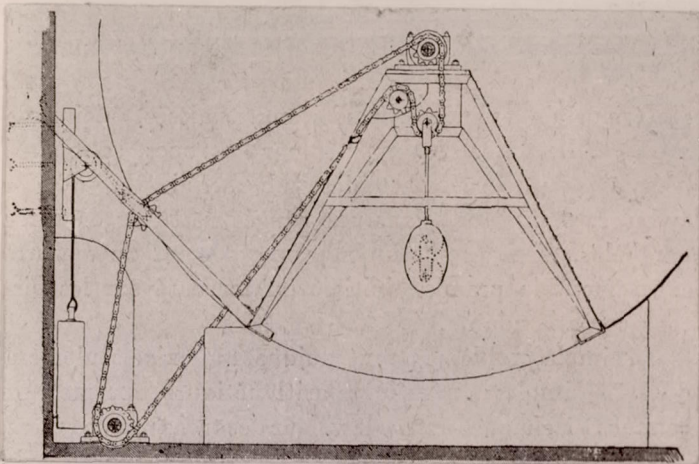


Fig. 6 Diagram of "Parmetro" or torque meter.

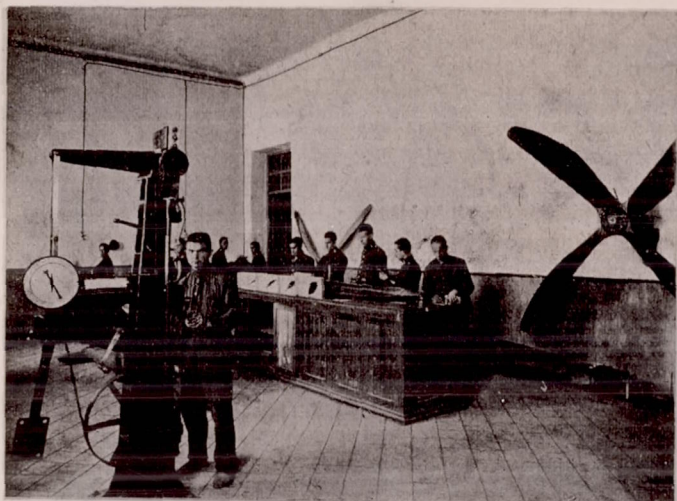


Fig. 9 Left, testing strength of cable. Right, propeller-balancing apparatus. At table, verifying accuracy of wing profiles with templets.



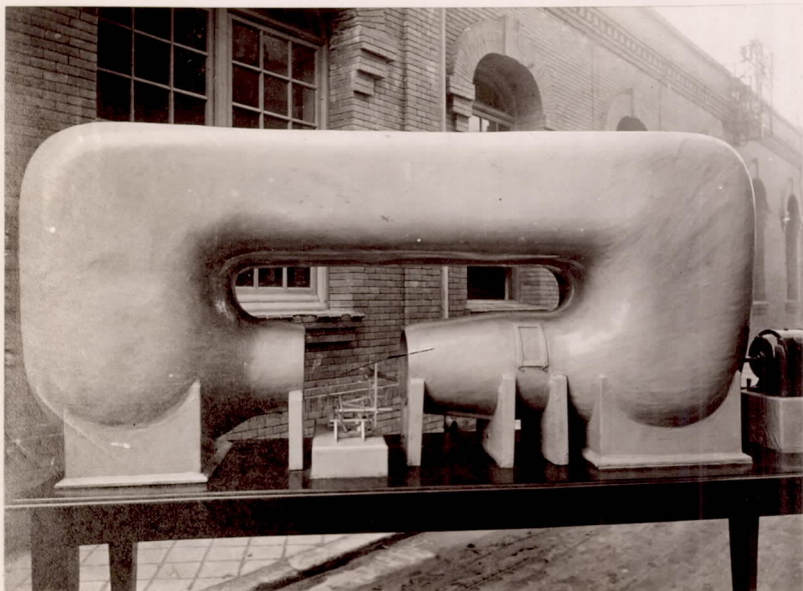


Fig.10 Model of Cuatro Vientos wind tunnel.

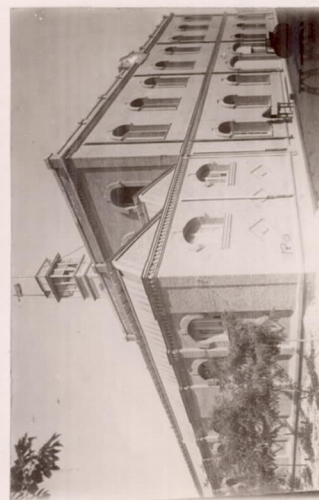


Fig.11 Aerodynamic laboratory at Cuatro Vientos.



Fig.12 View of the Herrera aerodynamic balance.

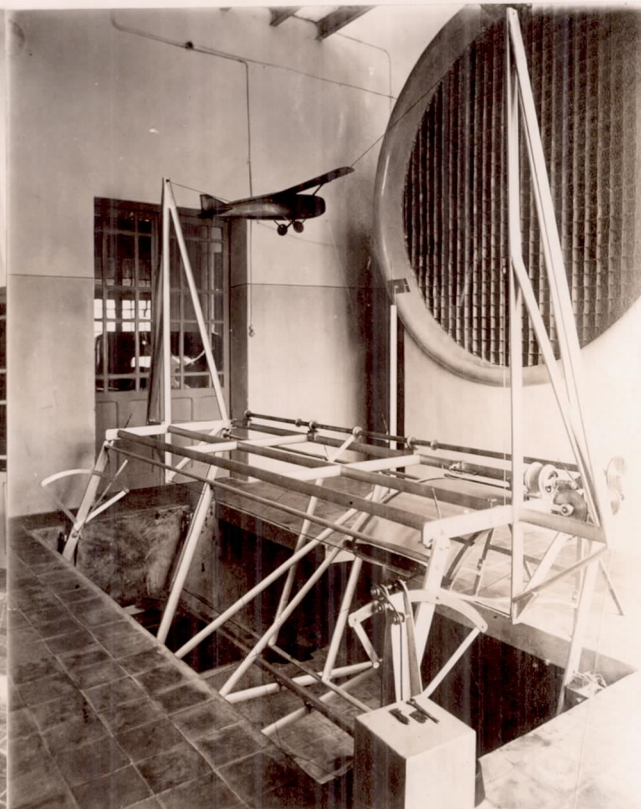


Fig.13 View of the Herrera aerodynamic balance.